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Article / Book Information

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Title(English)	Dissipative continuous time crystals originating from parity-time symmetry in open quantum systems
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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Exploration of novel non-equilibrium phases of matter or phase transitions and clarification of their mechanisms are important problems for non-equilibrium statistical physics. In particular, (continuous) time crystals that spontaneously break continuous time-translation symmetry into discrete time-translation symmetry are a typical example, and these have been observed in open quantum systems but proved to be impossible to exist in closed quantum systems. Here, continuous time crystals in open quantum systems are called dissipative continuous time crystals. In this thesis, we provide novel non-equilibrium phase transitions with anti-unitary symmetry breaking in Markovian open quantum systems and show that they can explain the mechanism of a class of dissipative continuous time crystals in open collective spin systems.

First, we give a novel phase transition similar to the parity-time (PT) phase transitions, which are studied in non-Hermitian systems well, for investigating a two-collective spin system with balanced gain and loss described by the GKSL (Gorini-Kossakowski-Sudarshan-Lindblad) equation. Here, a generator of the GKSL equation is called the Lindbladian. In the non-Hermitian PT phase transitions, for the Hamiltonian with the PT symmetry, the eigenvalues change from real to complex eigenvalues, thereby changing the dynamics from periodic oscillations to diverging or decaying dynamics, and the PT symmetry of the eigenstate is broken at the same parameter point. On the other hand, for the Lindbladian case, we show that when the Lindbladian has a PT symmetry, the Lindbladian spectrum transition, dynamics transition, and PT symmetry breaking of the stationary state occur at the same parameter point. Also, in the non-Hermitian PT phase transition, the transition point is known as the exceptional point where more than two eigenvectors coalesce. We will explain that the transition point is expected to be an exceptional point in the Lindbladian case as well. These properties are similar to those of non-Hermitian PT phase transitions. This dissipative phase transition is called the Lindbladian PT phase transition.

Next, we show the physical origin of the boundary time crystal (BTC) for specific models, which is a dissipative time crystal only in the thermodynamic limit. In particular, we focus on the dissipative one-collective spin model with transverse magnetic field and excitation loss (hereafter, we refer to this model as the Driven Dicke model). In the Driven Dicke model, the exact solution of the stationary state had already been found in 1979, and the static dissipative phase transition was known to occur. However, the mechanism of this phase transition is unclear. Also, the persistent oscillation appearing in this model was reaffirmed as the BTC in 2018, and this mechanism is also unclear.

In this thesis, we analytically show that the Driven Dicke model has the Lindbladian PT symmetry, and the PT symmetry breaking of the stationary state occurs at the point where BTC breaks down. Also, we numerically show a similar statement for another BTC (generalized Driven Dicke) model. Finally, using perturbation theory with degeneracy, we prove that BTC arises under weak dissipation for a class of one-collective spin systems only when gain and loss are balanced. These results indicate that there exist BTCs in collective spin systems originating from parity-time symmetry.

Furthermore, we give a simple and clear description of BTCs and the Lindbadian PT phase transitions using the Schwinger boson transformation. In particular, we show that when the Lindbladian has PT symmetry at the microscopic level, the Schwinger boson mean-field equation becomes a nonlinear Schrodinger equation with U (1) symmetry. Then, the effective nonlinear Hamiltonian has PT symmetry. Moreover, the continuous and discontinuous phase transitions can occur with non-linear PT symmetry breaking. Then, we demonstrate that all collective excitation modes are shown to be destabilized at the transition point using the linear stability analysis. As a result, the time-dependent phases appear, such as the swap or chiral phases, in which the amplitude or phase periodically oscillates, respectively. In particular, the phase where amplitudes are time-dependent (e.g., swap phase) corresponds to the time-crystalline (Lindbladian PT) phase in the notation of collective spin. Moreover, we show that critical exceptional points (CEPs), in which two excitation modes coalesce, emerge in the case of continuous phase transitions. Finally, we confirm the validity of these analyses by comparing them with numerical calculations. As a result, we can expect that the exceptional point also emerges for the Lindbladian.

Lastly, we summarize and mention the outlook on the BTCs and Lindbladian PT phase transitions. In particular, we mention the application of Lindbladian exceptional points. The PT phase transitions in non-Hermitian systems have been

used for many applications, such as sensors and lasers, by exploiting the properties of exceptional points. Then, the Lindbladian exceptional points may extend these to quantum systems. Our thesis will further our understanding of non-equilibrium phase transitions or phases of matter and help us develop applied techniques using exceptional points in open quantum systems.　(794 words)